AD-A283 564 COMBUSTION EFFICIENCY IN A DUAL-INLET SIDE-DUMP RAMJET 1/1
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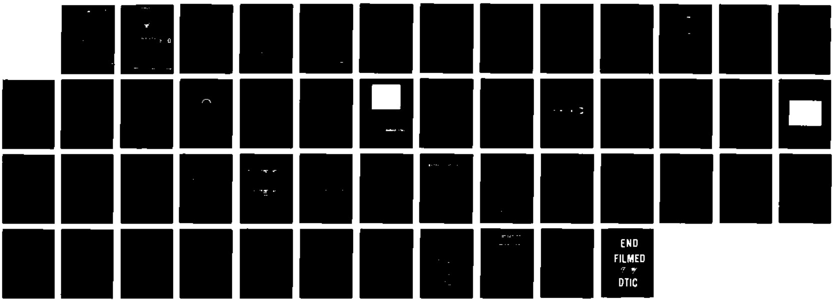

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NAVAL POSTGRADUATE SCHOOL
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THESIS

COMBUSTION EFFICIENCY
IN A DUAL-INLET SIDE-DUMP
RAMJET COMBUSTOR

By

Martin W. Deppe

June 1994

Thesis Advisor: D.W. Netzer

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	16 JUNE 1994	Master's Thesis; 9/93 to 6/94

4. TITLE AND SUBTITLE

COMBUSTION EFFICIENCY IN A DUAL-INLET SIDE-DUMP RAMJET COMBUSTOR

5. FUNDING NUMBERS

6. AUTHORS

Deppe, Martin W.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Air Warfare Center, Weapons Division
China Lake, CA 93555

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U. S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release, distribution is unlimited.

12b. DISTRIBUTION CODE

A

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS

Ramjet, Combustion, Side-Dump, JP-10, Poppet Atomizer

15. NUMBER OF PAGES

51

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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Combustion Efficiency

In A

Dual-Inlet Side-Dump Ramjet Combustor

by

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Lieutenant, United States Navy
B.S., United States Naval Academy, 1984

Submitted in partial fulfillment

of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

A dual, axially-in-line, side-dump, liquid-fueled ramjet combustor was designed and tested with varying fuel-air ratios, atomizer types, and air distributions between the two inlets. Particle size distributions produced by the atomizers were measured at the inlet duct plane. When operated in a contra-flow direction, all of the atomizers produced excellent atomization with a Sauter mean diameter less than 14 microns. The dual in-line inlets provided improved flammability limits and combustion efficiencies at lean fuel-air ratios when compared to single side-dump performance. Direct injection of approximately 20% of the fuel flow into the dome region was found to provide improved lean flammability limits for the single side-dump, but was not required with the dual inlets. The fuel distribution in the inlet duct required for good flammability limits and combustion efficiency was opposite to that required to prevent pressure oscillations, indicating that a dump plane aero-grid will often be necessary. A dump angle of 45° resulted in lower than desired combustion efficiencies, apparently due to poor mixing with the air from the aft inlet.

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I. INTRODUCTION

There are several propulsion systems that are well suited for tactical missile application. Tactical missile propulsion systems fall into two basic categories: those that ingest or breathe the outside air as an oxidizer (airbreathers) and those that carry oxidizer on board together with the fuel (rockets). Typically, the rocket is considered the simplest and as a result is usually selected for use in tactical missiles. However, as the speed and range requirements increase, ramjets become more attractive with the liquid fueled ramjet (LFRJ) providing the highest performance of the ramjet systems. Because it possesses the capability of versatility for mission optimization at high performance levels, it is the propulsion system of choice for long duration high speed (supersonic) flight over a wide operating regime [Ref. 16].

Since ramjets alone are unable to produce static thrust, they must be boosted to operational speed (usually by a solid rocket) at which time the ramjet ignites and sustains the required thrust for supersonic flight. Many of today's tactical missile concepts employ a more volumetrically efficient alternative known as the integral-rocket-ramjet (IRR) like that shown in Figure I-1, in which the solid rocket booster chamber is also used as the ramjet combustion chamber. Once the booster propellant burns away and the ramjet has been accelerated as mentioned earlier, the booster nozzle is ejected along with the ramjet inlet port covers, allowing ram air into the combustor. Liquid fuel is injected into the air flow via the inlet side dumps and flame stability is accomplished in the combustor chamber by aerodynamic flame holding in the mixing and recirculation zones [Ref. 13].

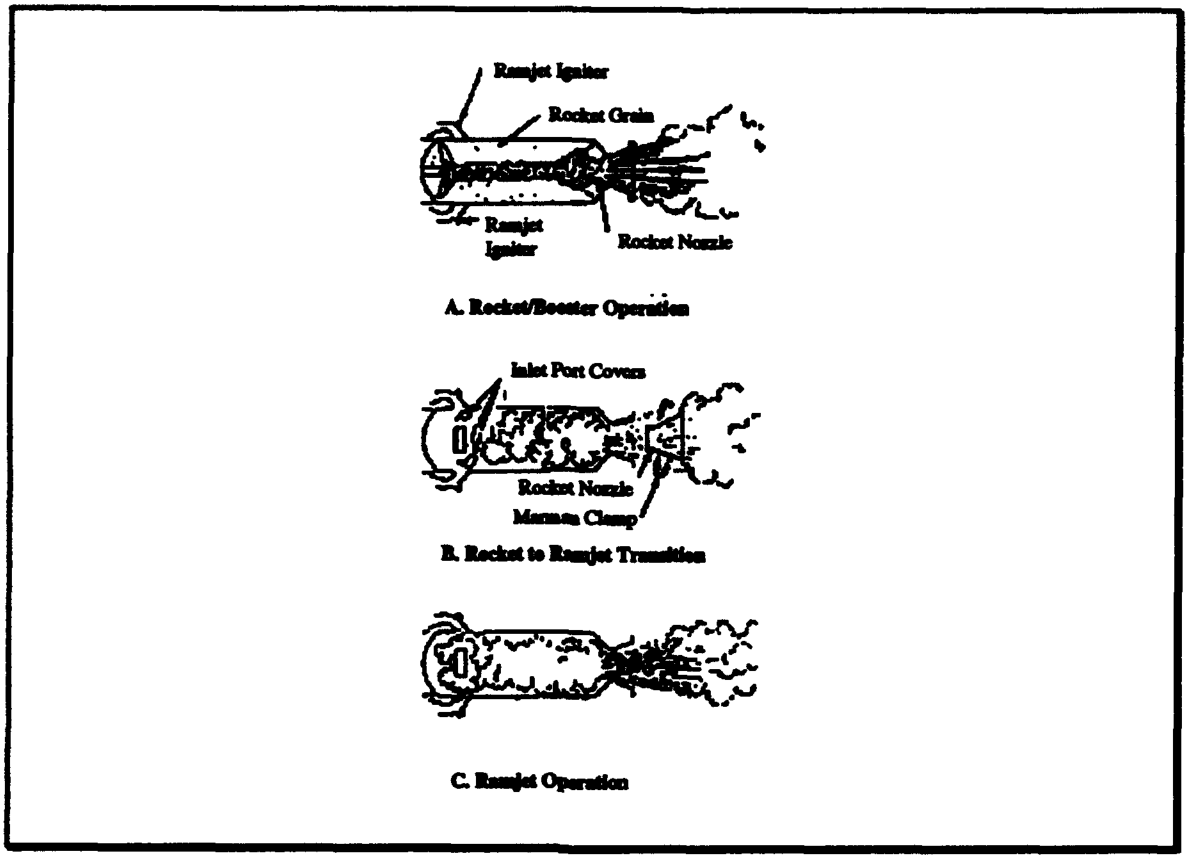

Figure I-1 Operating Sequence of Integral Rocket Ramjet [Ref. 16]

Flame stability is required over the desired operating limits. Recirculation zones provide areas of low local velocity to keep the flame stationary and ensure uniform burning while better mixing the fuel and inlet air. In early liquid fueled ramjets, the flames were generally stabilized by using either a combustor can or V-gutter flame holders located inside the combustor. The introduction of the IRR prohibits these types of flame stabilization devices since the combustor free volume is initially loaded with booster propellant [Netzer] as shown at the top of Figure I-1. Therefore, combustor internal aerodynamics becomes an important driver in the overall optimization of ramjet combustor design.

Optimizing ramjet combustor performance consists primarily of ensuring flame stability, efficient combustion, and minimizing total pressure losses, while remaining within size limitations imposed by application constraints. This requires rapid fuel vaporization and chemical reaction rates, and the proper distribution of fuel in the entering air. Generally, the higher the static temperature and pressure inside the combustor, the better the overall performance [Ref. 13]. Equivalence ratios must also be considered. Rich or lean blowoff in the combustor can limit acceleration and restrict the cruise Mach number. Typical ramjet operating envelopes necessitate a wide range of equivalence ratios and air mass flow rates. The design challenge is to maintain flammability and high combustion efficiency over a wide operating envelope.

Ramjet combustion inefficiencies or variations from ideal cycle analysis are readily defined though, in some cases, not easily quantified. Stagnation pressure losses in the subsonic section of the inlet diffuser result from wall friction and flow separation. Empirical data are most often used in their estimation. Heat addition in the combustor is also associated with a corresponding total pressure loss. The turning of inlet air and its rapid expansion into the combustion chamber also contribute to combustor inefficiency, though pressure loss associated with dump angle is relatively insensitive to dump angle changes between 45 and 90 degrees for entrance Mach numbers less than 0.3 [Ref. 11]. It has been found that aerodynamic grids can be used to prevent the flow separation associated with sudden expansion, and thereby improve inlet/combustor pressure recovery. These grids also serve to acoustically isolate the inlet air ducting from the combustion process in order to inhibit combustion pressure oscillations [Ref. 11]. Oscillatory combustion results when energy release processes within the combustor are able to amplify pressure and/or velocity disturbances and the combustor/inlet geometry and shock pattern are able to respond to further aggravate the disturbances. These oscillations can modify the thrust profile, unchoke the inlet diffuser, and can lead to flame-out or catastrophic structural failure [Ref. 11].

There have been several studies on ramjet side-dump combustion which serve to quantify various design attributes. One investigation used cold flow visualization methods in which Plexiglas models of ramjet combustors with varying dome lengths and associated inlet configurations were placed in a water tunnel and observed at comparable Reynolds numbers. Recirculation zones and mixing regions were identified with the use of bubble generation and laser sheet illumination. The results produced by Stull and Craig showed that variations in dome height greatly affect the head-end flow field but have little influence on the flow downstream of the inlet entry ducts. Follow-on combustion tests revealed that combustor performance was not sensitive to variations in dome height and only mildly affected by inlet entry angle [Ref. 14]. Zetterström and Sjöblom made a comparison study of two and four-inlet side-dump combustors. They found that the four-inlet combustor offered no advantage in performance levels though the two-inlet combustor was more prone to pressure oscillations. These oscillations could, however, be controlled by modifying the fuel injection in order to avoid fuel in the oscillating vortex system found (through water tunnel testing) near the dump plane. Buckley, Craig, and Obleski studied the effects of introducing swirl to the inlet prior to the dump plane and found that it had a dramatic effect on combustor performance while reducing the length of the combustion region in some cases by a factor of 2 [Ref. 2].

Salyer performed cold flow visualization studies on three different types of side-dump combustors: single-inlet side-dump, dual-inlet side-dump with inlets separated by 90°, and a dual in-line side-dump combustor. A non-intrusive laser-sheet, water tunnel, flow visualization apparatus was employed to qualitatively evaluate and determine optimum flame stabilization dome lengths and fuel injection locations. Salyer found that optimum dome lengths for good fuel distribution and steady mixing were between 0.3 and 1.4 combustor diameters. Shorter dome lengths resulted in unstable flow in the dome region and longer dome lengths resulted in poor mixing. He found that multiple fuel injection locations across the inlet dump plane were required for uniform fuel distribution in the downstream main combustion region. In order to distribute fuel into the dome or flame holding region, fuel injection on the upstream side of the inlet cross section was required. Most importantly, Salyer found that of the three combustor configurations explored, the dual in-line side-dump provided the highest potential for increasing performance over a wide range of operating conditions by varying the air mass flow through the two inlet dumps. This particular inlet/combustor configuration may well be suited to future ramjet tactical missile applications and is therefore worthy of extensive exploration.

The main objective of this present study was to validate the cold flow visualization data, taken by Salyer, in an actual dual in-line side-dump ramjet combustor using either fuel-tube and/or poppet atomizers as the fuel injection devices. The particle size distributions produced by the various injectors/atomizers over wide ranges of operating conditions were first determined using measurements of forward scattered light. The distribution of the fuel within the inlet duct was also determined in order to obtain the optimum locations for fuel injection. Tests were then conducted to measure the obtainable combustion efficiencies over a wide operating regime.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

A. APPARATUS

The equipment used in this present study consisted of a MALVERN 2600 HSD Laser Diffraction Particle Sizer, a MALVERN Mastersizer Particle Sizer, a dual axially-in-line side-dump ramjet combustor, fuel and air delivery systems, an ignition system, a computerized data acquisition system (MDAS), and an HP computer system for experiment control. The fuel used was JP-10, provided by the Naval Air Warfare Center, Weapons Division, China Lake, CA.

1. The Malvern Particle Sizers

The MALVERN 2600 [Ref. 10] and the Mastersizer [Ref. 9] particle sizers both operate on the principle of laser light scattering from an ensemble of particles. They are non-imaging optical systems because the sizing is accomplished without forming an image of the particles onto a detector. The forward scattered light, which occurs as the individual particles pass through the laser beam, is captured with a convex lens as shown in Figure II-1. Different sized particles will scatter the laser light at different angles without regard to speed or direction. The larger particles scatter the light at smaller angles and conversely, the smaller particles scatter light at larger angles, as shown in Figure II-2.

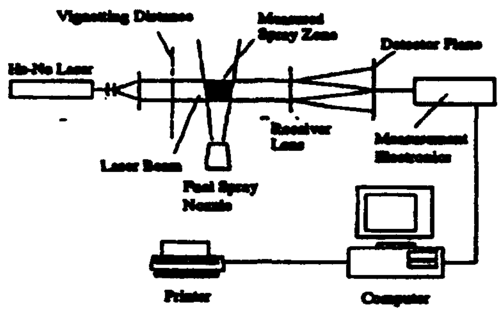

Figure II-1 MALVERN Particle Sizer Configuration [Ref. 10]

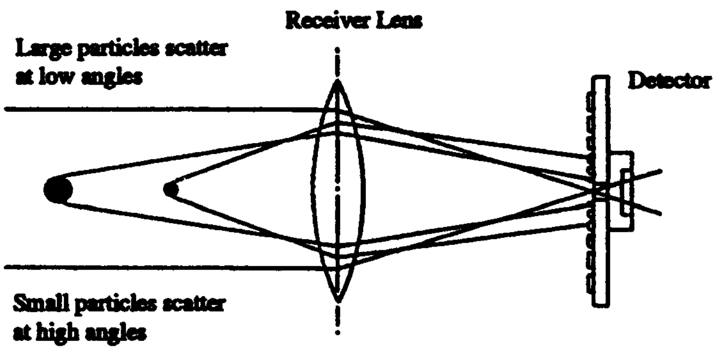

Figure II-2 Properties of the Scattered Light [Ref. 10]

The receiver lens operates as a Fourier transform lens, forming the far field diffraction pattern of the scattered light at its focal plane, where a detector composed of 31 concentric annular sectors receives the scattered light. In this configuration, wherever the particle is in the laser beam, its diffraction pattern is stationary and centered on the detector. Therefore, particle motion or cross-sectional position within the beam has no effect on the size measurements. (See Figure II-3) Using a 300 mm receiver lens, the Malvern 2600 can measure particle sizes from 5.8 to 564 microns and make estimates down to 1.2 microns. The Mastersizer, with a 300 mm lens, can measure particle sizes from 1.2 to 600 microns. The main difference between these two similar instruments is the Mastersizer's incorporation of "Mie Theory" corrections for light scattering from the smaller particles.

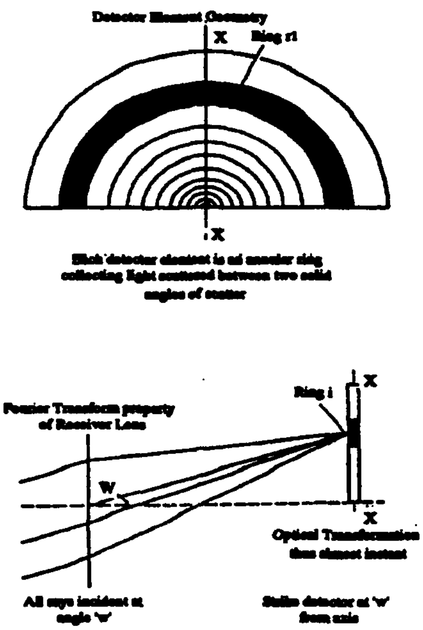

Figure II-3 Properties of the Range Lens [Ref. 10]

The ratio of refractive index of the dispersant and the particle, and the particle absorption index must be provided to the computer for the highest degree of accuracy. Useful output from both sizing systems consists of the volume distribution and the number distribution of particles measured. The volume distribution provides an estimate of how much of the sample volume is made up of particles within specific ranges of diameters. The number distribution provides an estimate of how many of the measured particles on a percentage basis have diameters within the same specific ranges.

2. The Fuel Delivery System

The fuel delivery system as shown in Figure II-4 consisted of a nitrogen-pressurized fuel tank with a fuel capacity of 0.9 gallons of JP-10. The fuel passed through a cavitating venturi to maintain a constant mass flow rate while under the influence of any back pressure from the combustion chamber and/or the fuel atomizers. Several venturis of different throat sizes were used as fuel-flow rate requirements were changed. Each venturi was individually calibrated to determine the mass flow rate as a function of nitrogen pressure. As long as the pressure upstream the venturi was at least 150 psig above the pressure downstream of the venturi, the fuel mass flow rate would remain independent of downstream pressure. A plot of the calibration curves for four of the venturis used is shown in Figure II-5.

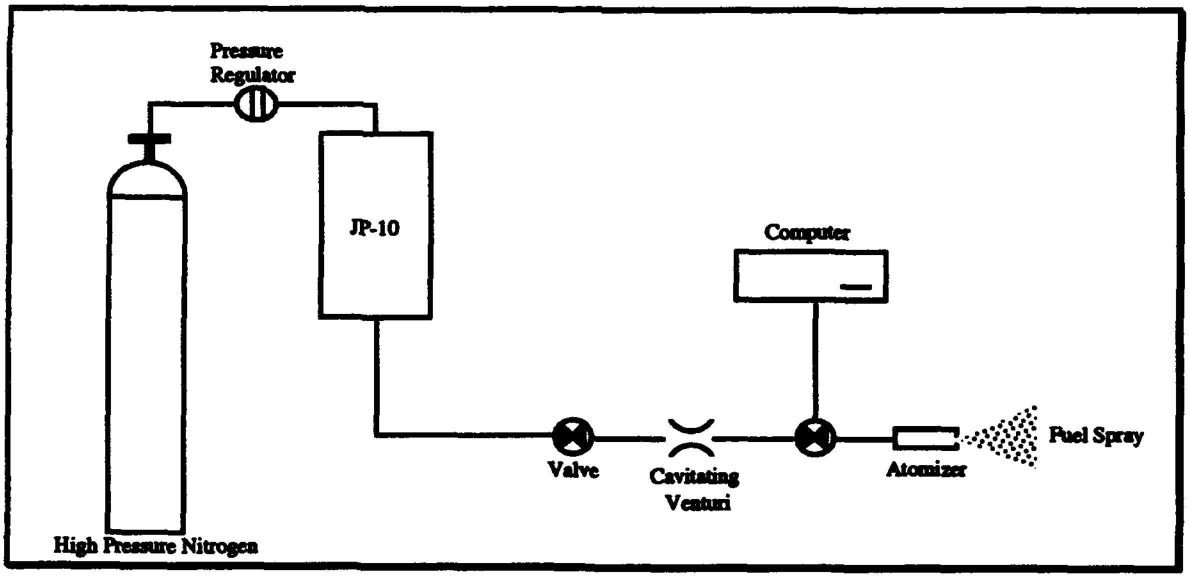

Figure II-4 Fuel Delivery System [Modified from Ref. 15]

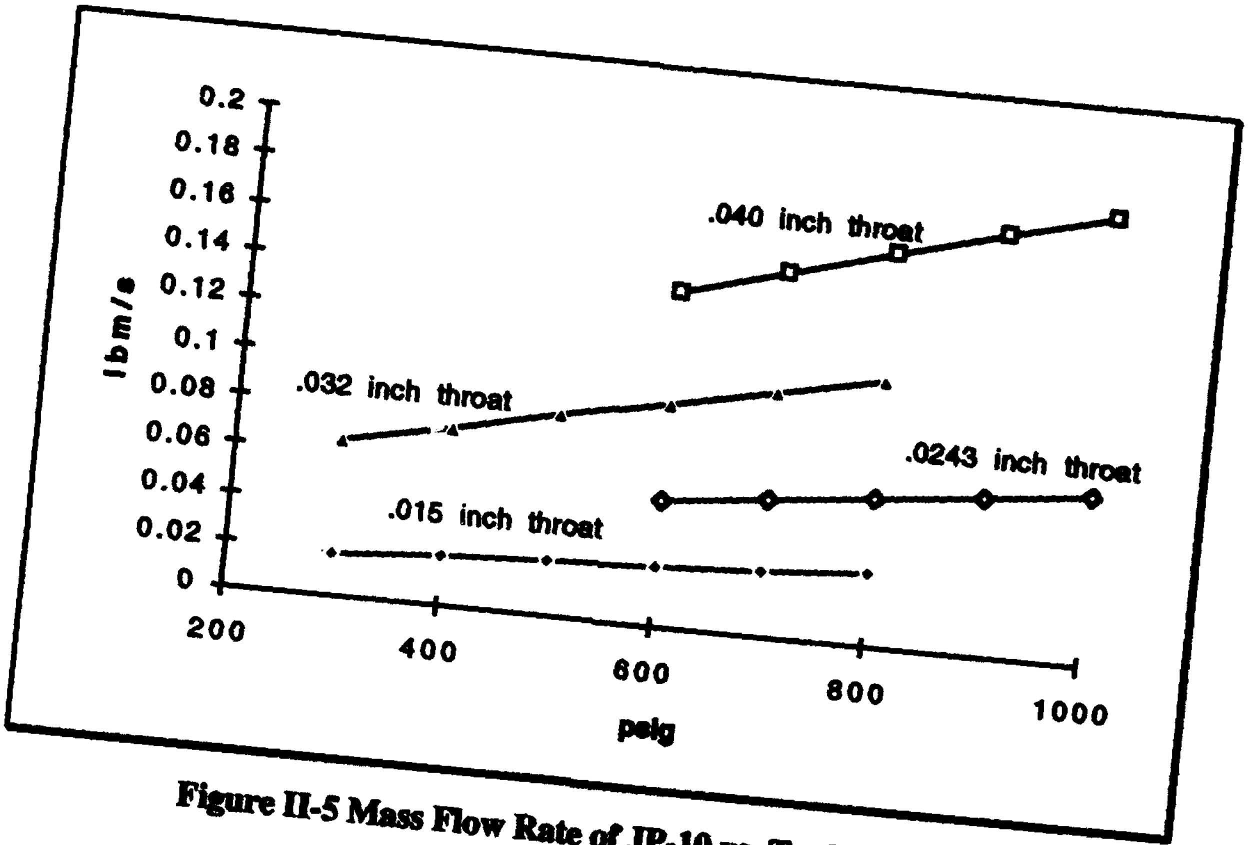

Figure II-5 Mass Flow Rate of JP-10 vs. Tank Pressure

Two poppet atomizers and a fuel-tube atomizer were used as the fuel injection devices throughout the study. Poppet atomizers, as seen in Figure II-6, are pintle type injectors that provide varying mass flow rates depending on the pressure drop across the atomizer. A higher pressure drop causes the pintle to move further forward and provide a larger orifice for fuel passage. This results in a higher mass flow rate of fuel. The two poppet atomizers, manufactured by Engineering Products Company (EPCO), began operating with 50 and 200 psi pressure drops, respectively. Water mass flow rates as a function of pressure drop are listed below in Table II-1 and were provided by the manufacturer.

Figure II-6 EPCO Poppet Atomizers

Table II-1 POPPET ATOMIZER WATER MASS FLOW RATES

50 Psi Atomizer		200 Psi Atomizer	
Pres. Drop (psi)	**Mdot (lbm/s)**	**Pres. Drop (psi)**	**Mdot (lbm/s)**
50	0	200	0
100	0.040	300	0.100
200	0.123	400	0.200
300	0.205	500	0.300
400	0.287	600	0.400
500	0.369		

The fuel-tube atomizer as seen in Figure II-7 was simply a 1.5 inch section of 1/4 inch diameter steel tubing with two columns of four holes tapped evenly spaced along its length with the two columns separated by 90°. The bottom of the tube was soldered closed so that fuel could only escape through the columns of holes. The design was based upon the optimum locations for fuel penetration determined by Salyer in a water tunnel flow visualization investigation [Ref. 13]. As the pressure drop across the tube increases, more fuel is forced through the holes increasing the mass flow rate.

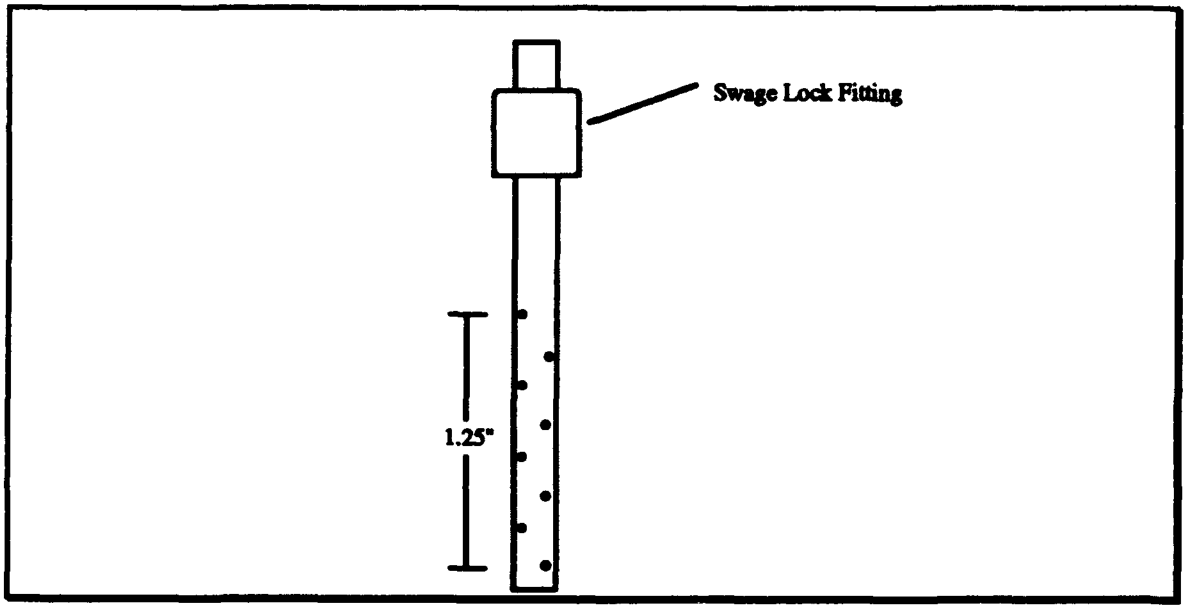

Figure II-7 Fuel-tube Atomizer

3. The Air Delivery System

The air delivery system as seen in Figure II-8 was designed to provide a maximum of 1.5 lbm/s of vitiated air at temperatures to 1160°R. The air was supplied via a high pressure tank farm located outside the test cell. The air-flow rate was controlled by a dome loaded, pressure regulator and a properly sized sonic choke placed just downstream. The air was heated by a hydrogen-fueled air heater to temperatures comparable to those that would occur at a Mach number of about 3.0. Make-up oxygen was injected into the air upstream of the air heater in proportion to the amount of hydrogen that was burning, so that the combustor air would have the normal 21% molar oxygen content. Various pressure transducers and thermocouples were located as shown in Figure II-8 so that accurate mass flow rates of the air, hydrogen, and oxygen could be monitored throughout the test runs.

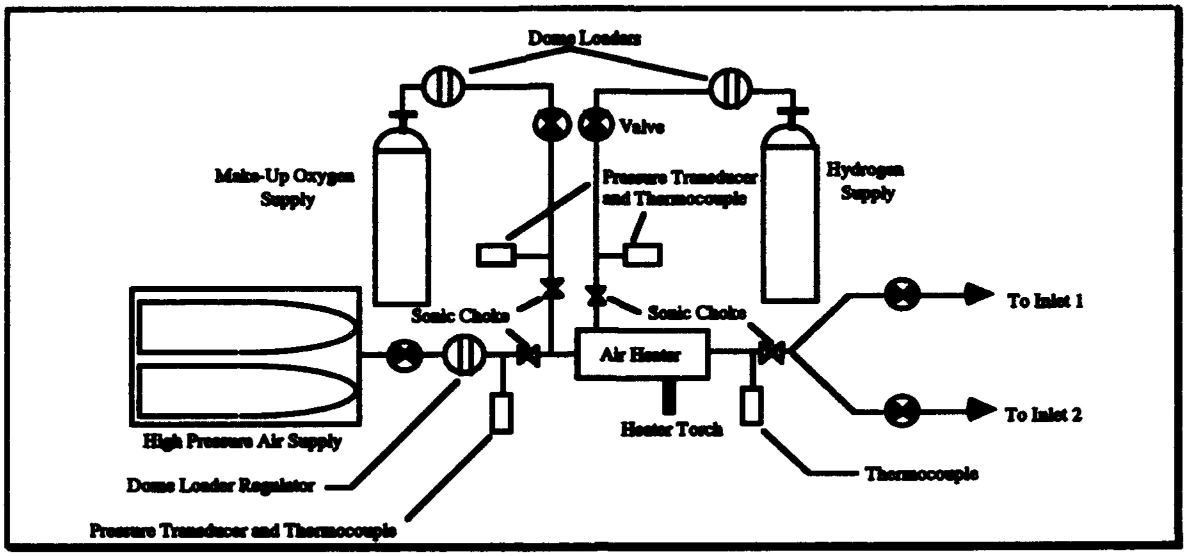

Figure II-8 Air Delivery System [Modified from Ref. 15]

4. The Combustor

A dual, circular-inlet, axially-in-line, side-dump ramjet combustor as seen in Figure II-9 was designed and used for this study. Two 1.5 inch inner diameter inlet pipes, axially separated by 4 inches, were used. The center of the upstream inlet was located 2.375 inches from the dome plate. The inlets were welded to a 3.25 inch inner diameter combustor that measured 19 inches from the head end (dome) to the nozzle entrance. A dome length of 2.375 inches (0.73D) was selected [Ref. 13]. Fuel atomizers were located at various positions along the inlet pipes and these are discussed further in the experimental procedures section. The flow pattern through such a combustor is characterized by three distinct flow regions that occur sequentially along the longitudinal axis. They are comprised of the dome region (located from the head end to the beginning of the upstream inlet dump plane), the ancillary region (located between the two inlet dump planes), and the main combustion region (located from the end of the downstream inlet dump plane to the nozzle entrance) [Ref. 13]. The dome region, or recirculation zone upstream of the forward inlet, served as the flame holder and provided the flame stabilization. The ancillary and main combustion regions exhibit various amounts of swirl and twisting in the flow, providing increased mixing and fuel distribution.

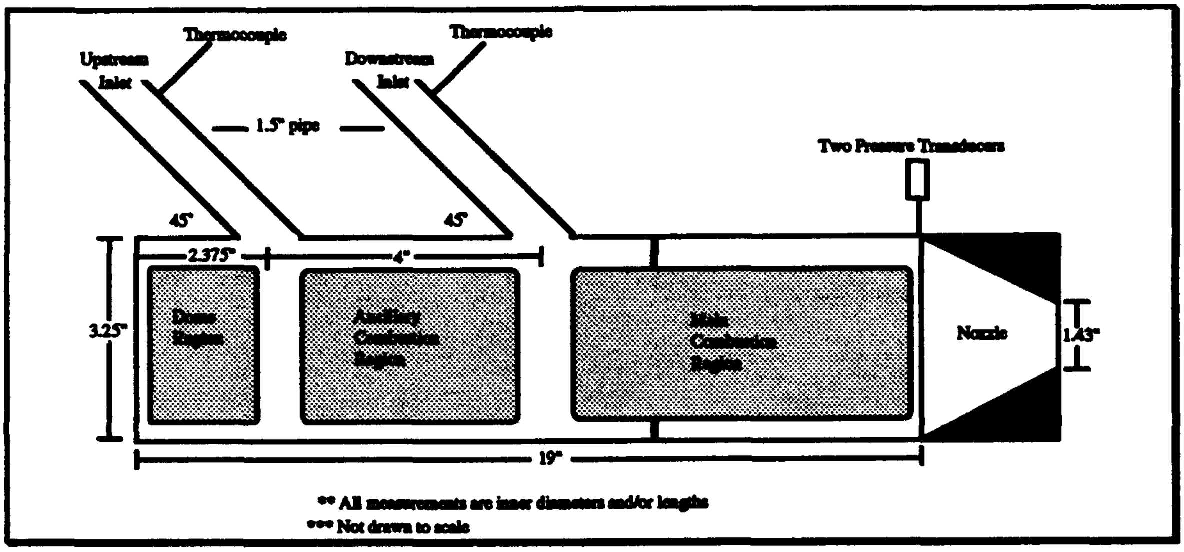

Figure II-9 Dual-Inlet Side-Dump Combustor Configuration

5. The Data Acquisition System (MDAS)

A Kaye 7000 Modular Data Acquisition System was used to collect the dynamic data throughout each of the combustor test runs. It was configured to simultaneously sample six pressure transducers, five thermocouples, and a thrust load cell, at a rate of 25 readings per second. The data were fed into a standard IBM 386 computer which used DCALC software to display readings and perform calculations to derive and output quantities such as mass flow rate, pressure, temperature, and thrust.

B. PROCEDURES

This study was accomplished via two distinct phases of data collection. First, the fuel spray from the different atomizers had to be characterized, over a wide range of operating conditions, in order to determine the optimum placement of the fuel atomizers in the inlet dumps. Then, ramjet combustion tests were performed with different combinations of atomizers while varying the air-flow rate between the forward and aft inlets.

1. Atomizer Fuel Spray Characterization

The particle size distribution produced by the 50 and 200 psi poppet atomizers and the fuel-tube atomizer were measured using the Malvern 2600. Measurements were first taken with the fuel atomizers spraying into ambient conditions at various fuel mass flow rates. These data were to serve as a control before subjecting the spray to actual air-flow conditions. The experimental configuration for these measurements is shown below in Figure II-10.

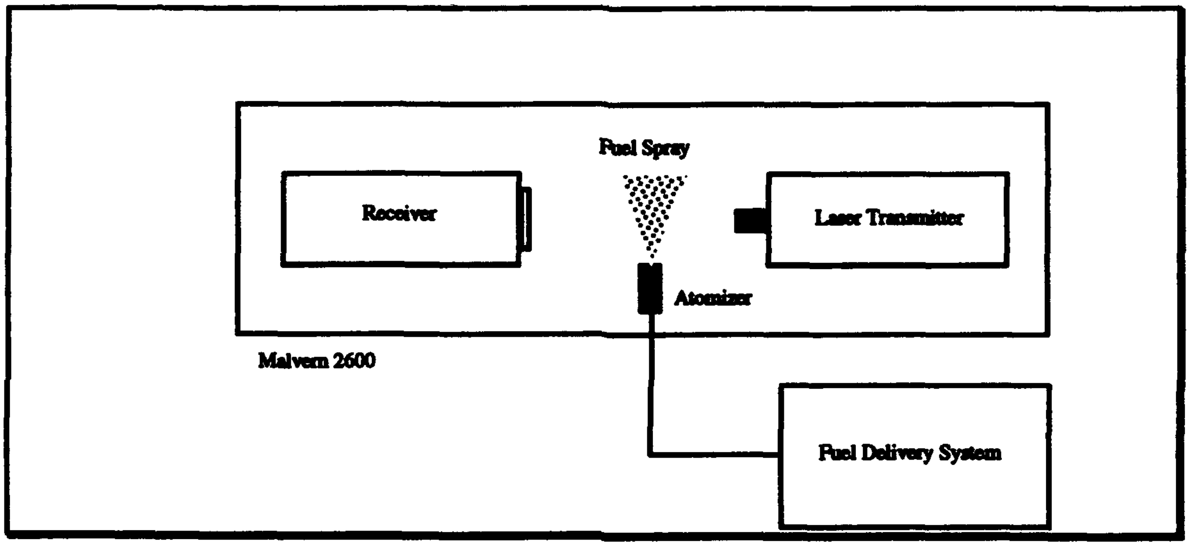

Figure II-10 Particle Size Measurement Configuration for Ambient Conditions

With no air flow, the fuel-tube atomizer simply squirted the fuel into the ambient air and exhibited poor atomization qualities. Malvern particle size measurements were therefore not performed. The 50 and 200 psi atomizers did exhibit atomization qualities in ambient conditions. Particle size measurements were made until fuel-flow rates were high enough to obscure too large a portion of the laser beam for accurate Malvern measurement. Great care was taken to ensure that no spray droplets contaminated the protective plate glass covering both the receiver lens and the transmitter, as this would have altered the data.

A model of the inlet duct was constructed with the dump plane cut at a 45° angle (as in the actual combustor). The 50 and 200 psi atomizers were first mounted contra-flow, i.e. opposing the air flow, and centered in the pipe. The inlet pipe configuration was then attached to the air delivery system. Cold air at both 0.5 and 1.0 lbm/s was blown over the atomizers while a video camera recorded the fuel spray patterns at various fuel-flow rates. Optimally, the fuel would spread just shy of the inner diameter of the inlet pipe as it reached the dump plane. If it spread more than this, fuel could accumulate on the inner wall of the inlet and increase the fuel particle size. If it spread less than this, maximum distribution of fuel would not be achieved in the combustor, as part of the inlet dump air would not contain any fuel. From earlier work [Ref. 13], in order to get any fuel into the recirculation zone or dome region, the fuel had to arrive near the leading edge of the forward inlet dump plane. This would not occur if the fuel did not spread almost all the way to the inlet wall.

The same procedure was repeated, this time, with the atomizers mounted perpendicular to the air flow and flush with the inner pipe wall. By comparing the fuel spray patterns at different operating conditions, an optimum placement of each atomizer relative to the inlet-dump plane could be determined. Both the contra and perpendicular fuel-flow configurations are pictured in Figure II-11.

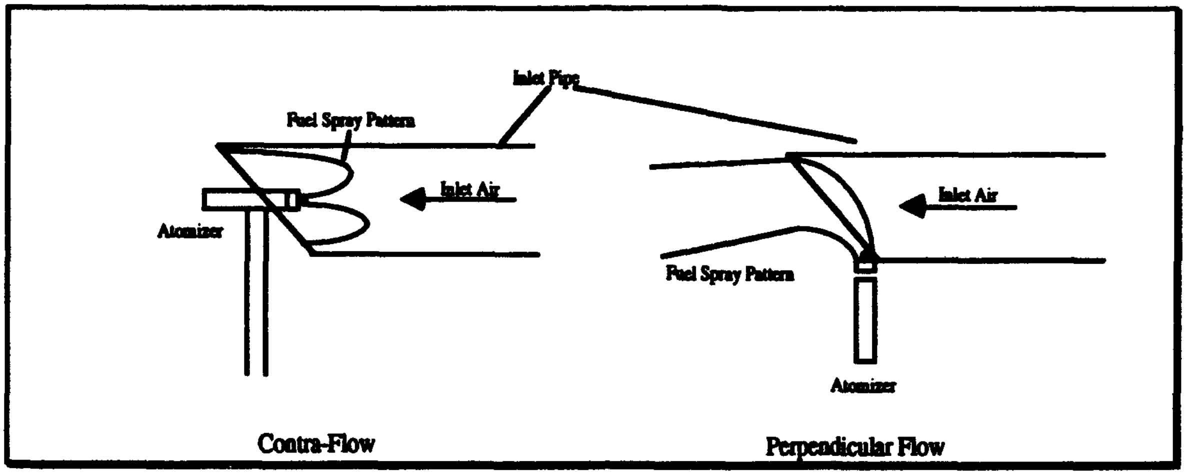

Figure II-11 Contra and Perpendicular Fuel-Flow Configurations

The contra-flow configuration pictured above (with the 50 psi atomizer) was utilized once again and particle size measurements were taken at the exit of the inlet dump with the Malvern 2600. Fuel and air-flow rates were varied over a wide range of operating conditions. Measurements were taken with and without the air-heater engaged. The fuel-tube atomizer was also examined under the same hot flow conditions, however it was installed through the center of the inlet dump cross-section and spanned from one side of the pipe to the other. The two lines of atomizer holes were directed upstream at the 10 and 2 o'clock positions (12 o'clock pointed directly upstream).

2. Ramjet Combustion

The sub-scale, dual-inlet side-dump liquid-fuel ramjet combustor, mounted on the thrust stand, is shown in Figure II-12. The 50 psi poppet atomizer was installed contra-flow in the upstream inlet for the initial testing. The downstream inlet was initially closed and left without a fuel atomizer. In this configuration the combustor would act as if it had only a single side-dump.

Several tests were conducted at various fuel and air-flow rates covering a wide range of operating conditions.

In the next test series, the downstream inlet was opened and equal diameter sonic chokes were installed in each line. This ensured that equal air-flow rates would enter the combustor through each inlet. The same series of tests were conducted in this new configuration so a comparison could be made between single and dual side-dump performances.

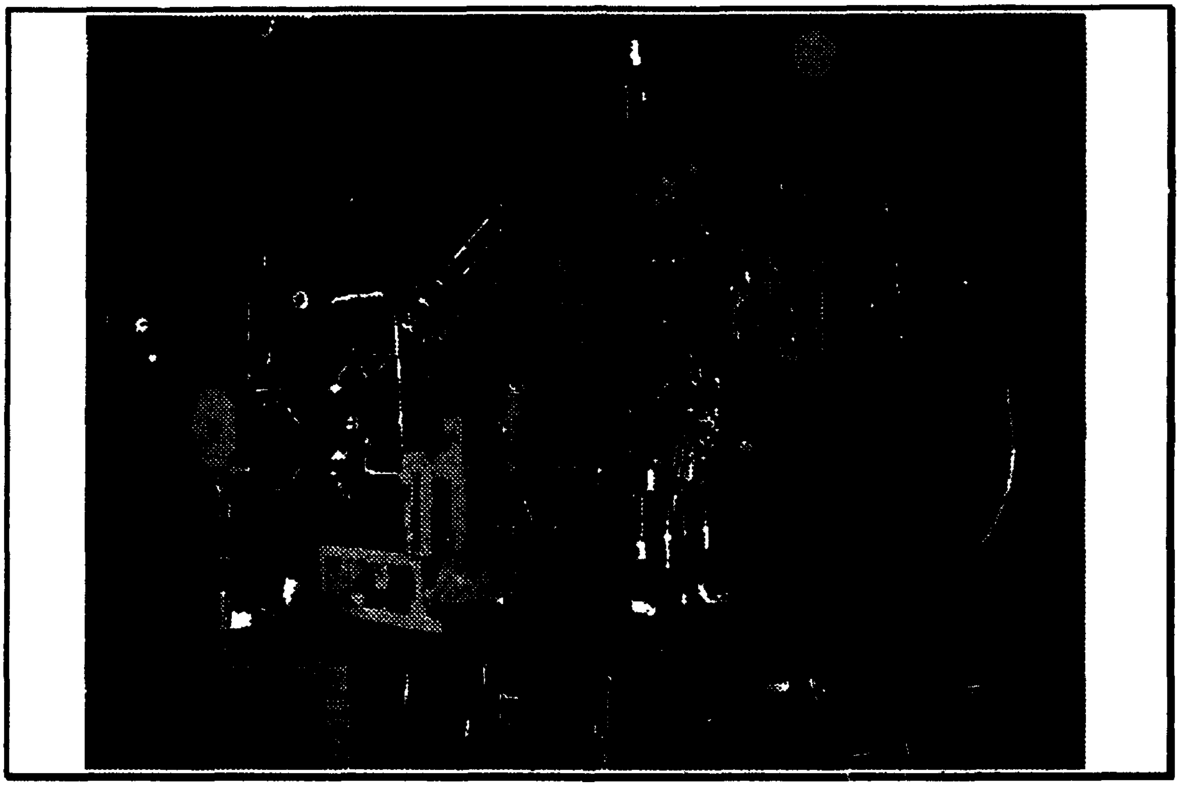

Figure II-12 Dual-Inlet Side-Dump Ramjet Combustor

In the low fuel-flow rate test conditions, it was apparent that insufficient fuel spread to the inlet wall to penetrate the recirculation zone. Without sufficient fuel in the recirculation zone, motor ignition as well as flame stabilization was impossible. To adjust for this fuel deficiency in the recirculation zone, a fuel injection tube measuring 0.02 inches in diameter was installed at the side of the dome region and positioned so that the fuel would spray circumferentially into the recirculation zone. Fuel was supplied to the dome injection tube via the same fuel system that supplied the poppet atomizer. Total fuel-flow rate was still controlled by the cavitating venturi, but with this modification, approximately 21% of the fuel was diverted to the dome injection tube.

In an attempt to maximize fuel distribution throughout the combustor, the fuel-tube atomizer (Figure II-7) was installed in the downstream inlet in conjunction with the poppet atomizer in the upstream inlet. A separate (though different size) cavitating venturi was placed upstream of each atomizer in order to control fuel-flow rates. Upstream pressure for each venturi came from a single source and was therefore the same for any particular test. Approximately 68% of the fuel went to the forward inlet and the remaining 32% was directed to the downstream inlet.

Then, the poppet atomizer was removed and the fuel-tube atomizer (Figure II-7) was moved from the downstream to the upstream inlet. The same series of tests were again conducted so a comparison could be made between the poppet and fuel-tube atomizers.

Finally, in an effort to suppress low frequency combustion pressure oscillations (approximately 150 Hz), an aero-grid was installed approximately 7 inches upstream of the fuel-tube atomizer in the forward inlet. The grid consisted of a stainless steel plate with 0.089 inch diameter holes drilled through it to provide a flow blockage of 39%. This was installed to decouple the inlet flow from the combustor. The first-longitudinal mode of the combustor was at a significantly higher frequency than that which was observed. Any remaining low frequency oscillation would then probably be due to coupling between the energy release and the shedding vortices at the dump plane. Aero-grids located at the dump plane are often used to eliminate the latter oscillations.

3. Efficiency Calculations

Efficiency in all cases was calculated based on temperature rise in the combustor and was given by the equation:

$$\eta_{\Delta T} = \frac{T_{t4exp} - T_{t2}}{T_{t4th} - T_{t2}}$$

The measured mass flow rates of air, hydrogen, oxygen (vitiated air constituents) and JP-10 (a function of upstream pressure and venturi throat size) along with T_{t2} (stagnation inlet temperature) and P_4 (chamber static pressure) were input to the PEPCODE [Cruise] for known nozzle contraction area ratio (A_4/A_5C_d). The discharge coefficient was determined from pre-test hot air-flow measurements. Outputs from the code were the theoretical stagnation combustor temperature ($T_{t4,th}$), the equivalent gamma for a shifting equilibrium process [Ref. 1], the gas constant of the combustion products, and the chamber Mach number.

$T_{t4,exp}$ is the experimental stagnation temperature in the combustor which cannot be directly measured with a high degree of accuracy. However, it can be calculated from the measured thrust and/or the measured chamber pressure [Ref. 1]

Relatively high pressure oscillations were present on many of the tests, making calculation of the average chamber pressure difficult. However, the measured thrust showed much less oscillation due to damping in the stand. For this reason, the efficiencies reported in this study are those based on the direct thrust measurement.

Based upon a thrust measurement, using a converging choked nozzle:

$$T_{t4,exp} = \gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\frac{C^{*2}_{exp}}{R_4}$$

γ = shifting equilibrium process gamma

R_4 = gas constant obtained from PEPCODE

$$C^*_{exp} = \frac{P_{t4}A_5C_d}{\dot{m}_4}$$

$$P_{t4} = \frac{Thrust + p_{amb}A_5}{(1+\gamma C_d)A_5}\left(\frac{\gamma+1}{2}\right)^{\left(\frac{\gamma}{\gamma-1}\right)}$$

III. RESULTS

A. ATOMIZER PERFORMANCE

The particle size distributions produced by the different atomizers were desired in order to determine if a correlation with combustion efficiency could be made. The Naval Air Warfare Center, Weapons Division, China Lake, CA also needed the data for both their full scale testing, and for input to their CFD combustor code.

1. Atomizer Performance In Ambient Conditions

Particle size data were taken on both the 50 and 200 psi poppet atomizers with the Malvern 2600. The atomizer tips were located 2.5 inches upstream from the traversing laser beam center. The fuel-tube atomizer had poor atomizing qualities without the use of surrounding airflow and was not included in this phase of testing. The data were taken as a function of pressure drop across the atomizer and are shown below in Tables III-1 and III-2. An increase in pressure drop corresponds to an increase in fuel mass flow rate. All of the higher fuel-flow rates resulted in very dense sprays. Measurements made with the resulting high obscurations of the laser beam are not accurate for the mass-in-mode (percentage of particle mass within specific size ranges), but the mode peaks are generally located accurately.

For both atomizers, the Sauter mean particle diameter (D_{32}) decreased with increasing pressure drop across the atomizer as seen in Figure III-1. In the tables above, the volume distribution peaks represent specific particle sizes that account for the majority of the total volume of fuel droplet mass and appeared to be approximately constant for each specific atomizer over the range of pressure drops. The fourth column represents the Malvern estimation of the % of particle volume contained in particles with diameters that were below the lower particle size limit of 5.8 microns. The final column is a measurement of how much incident laser light was not received by the detector due to scattering and/or absorption.

Table III-1 50 PSI ATOMIZER PERFORMANCE (AMBIENT AIR)

Pres. Drop (psig)	D_{32} (microns)	Volume Distribution Peaks (microns)	% Volume less than 5.8 microns	% Obscuration
75	81	120	0	31
125	61	40, 130	0.7	69
250	58	120	0.4	80*
400	33	43, 90	1.6	95*

* High obscuration, unknown accuracy of D_{32}

Table III-2 200 PSI ATOMIZER PERFORMANCE (AMBIENT AIR)

Pres. Drop (psig)	D_{32} (microns)	Volume Distribution Peaks (microns)	% Volume less than 5.8 microns	% Obscuration
250	55	37, 120	0.2	47
300	37	40, 90	1.1	84*
400	39	40, 90	1.2	95*
500	30	40, 77	2.5	97*

* High obscuration, unknown accuracy of D_{32}

The spray angle of each poppet atomizer was measured from the video image (two dimensionally) while spraying into ambient conditions over a range of fuel-flow rates. The angle for both atomizers was constant at 65±5° and was not a function of fuel-flow rate.

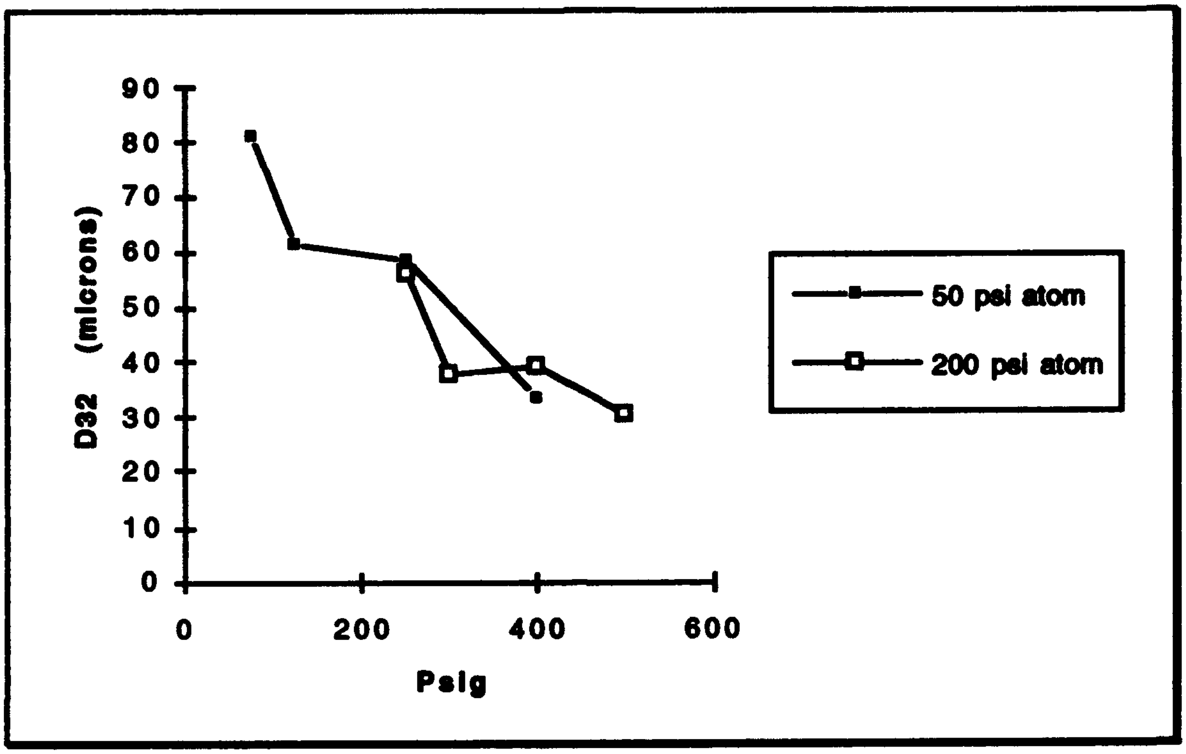

Figure III-1 D_{32} vs ΔP for 50 and 200 psi Atomizers in Ambient Conditions

2. Fuel Atomizer Performance With Surrounding Air Flow

Both poppet atomizers were individually mounted contra-flow in a mock-up inlet pipe which was then connected to the air supply system. Air-flow rates of 0.5 and 1.0 lbm/s were passed over the atomizers as they were subjected to a range of fuel-flow rates. The higher the air-flow rate, the less the fuel spread in the inlet pipe. For both atomizers at the 1.0 lbm/s air-flow rate and the lower fuel-flow rates (ΔP of 75 and 125 psi for the 50 psi atomizer and 250 psi for the 200 psi atomizer), the fuel did not spread to the inlet pipe wall prior to reaching the dump plane. This could leave the recirculation zone without sufficient fuel and, therefore, degrade the flame holding and may also limit the fuel distribution within the combustor resulting in lower efficiencies.

The atomizers were then mounted perpendicular to the air flow and subjected to the same operating conditions as with the contra-flow mounting. Again, poor fuel distribution was noted at the lower fuel-flow rates mentioned above, but the distribution improved as the fuel-flow rate was increased. However, it was uncertain as to how evenly the fuel was distributed throughout the inlet dump plane with perpendicular mounting as it seemed reasonable that a much higher concentration of fuel would be at the wall opposite the atomizer.

Particle size data were taken on the 50 psi poppet atomizer (Table III-3) and also on the fuel-tube atomizer (Table III-4) while subjected to 0.5 and 1.0 lbm/s mass flow rate of air. The 200 psi atomizer was not included, in the interest of time, since its minimum mass flow rate of fuel was too high for use in the sub-scale motor used in the ramjet combustion performance tests. The 50 psi atomizer was mounted contra-flow with the atomizer tip located 3.5 inches upstream from the traversing laser beam. The air temperature was varied in some tests to determine its effect on the particle size distribution. If no apparent effect was noted, subsequent measurements would have been made using cold air in order to save vitiator fuel. Increased temperature, however, significantly reduced the particle size and, therefore, subsequent measurements were made hot at approximately 550°F. The results are shown in Tables III-3 and III-4.

For any particular air-flow rate and pressure drop across the atomizer, an increase in air temperature above ambient reduced the mean particle size (Figure III-2). Contrary to the measurements made under ambient flow conditions, the pressure drop across the atomizer had little effect on the mean particle size for the contra-flow, hot air condition.

Table III-3 50 PSI ATOMIZER WITH SURROUNDING AIR FLOW

Mdot Air (lbm/s)	ΔP (psig)	Air Temp (°F)	D_{32} (μ)	D_{max} (μ)	Vol. Peaks (μ)	% <5.8 (μ)	% Obs.	Kill-Data
0.5	75	550	3.7	40	<5.8	68.5	29	5,0
0.5	90	38	12.5	96	7,20,32	7.4	55	----
0.5	90	250	9.1	40	<5.8,15	11.2	28	----
0.5	125	38	10.2	71	<5.8,20 ,32	11.1	77	----
0.5	125	530	6.7	40	<5.8,11	23.3	40	----
0.5	200	530	7.0	40	<5.8,11	19.8	46	----
0.5	250	530	6.7	40	<5.8,11	22.7	42	----
1.0	75	550	6.5	22	<5.8,11	24.3	7	5,0
1.0	90	400	4.1	19	<5.8, 8.5	55.4	40	----
1.0	90	450	4.0	16	<5.8, 8.5	59.3	36	5,0
1.0	125	39	7.8	40	<5.8, 17.5	17.2	76	----
1.0	125	542	3.7	16	<5.8, 9.5	67.5	68	5,0
1.0	150	541	3.8	16	<5.8, 8.5	64.4	80	5,0
1.0	250	550	3.6	40	<5.8	70.5	61	5,0

Except for the lowest fuel-flow rate, an increase in air mass flow rate decreased the mean particle size (Figure III-3). It also reduced the maximum particle size and increased the mass percentage with diameters less than 6 microns (Table III-3).

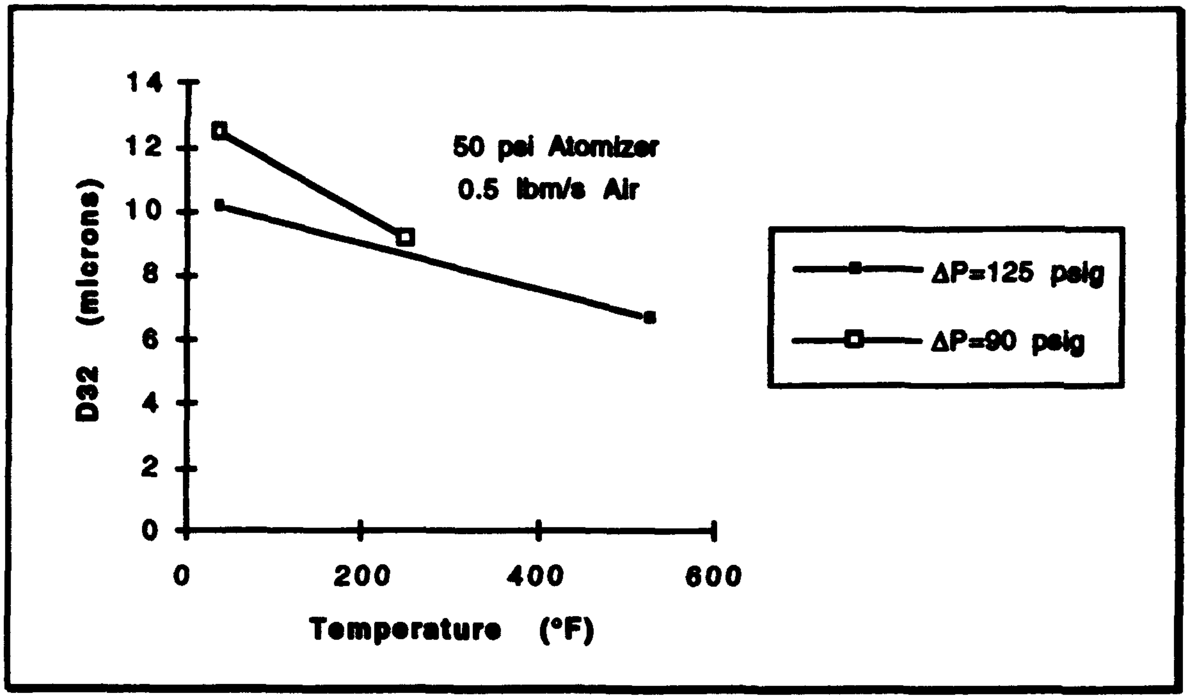

Figure III-2 Temperature Effects on Particle Size

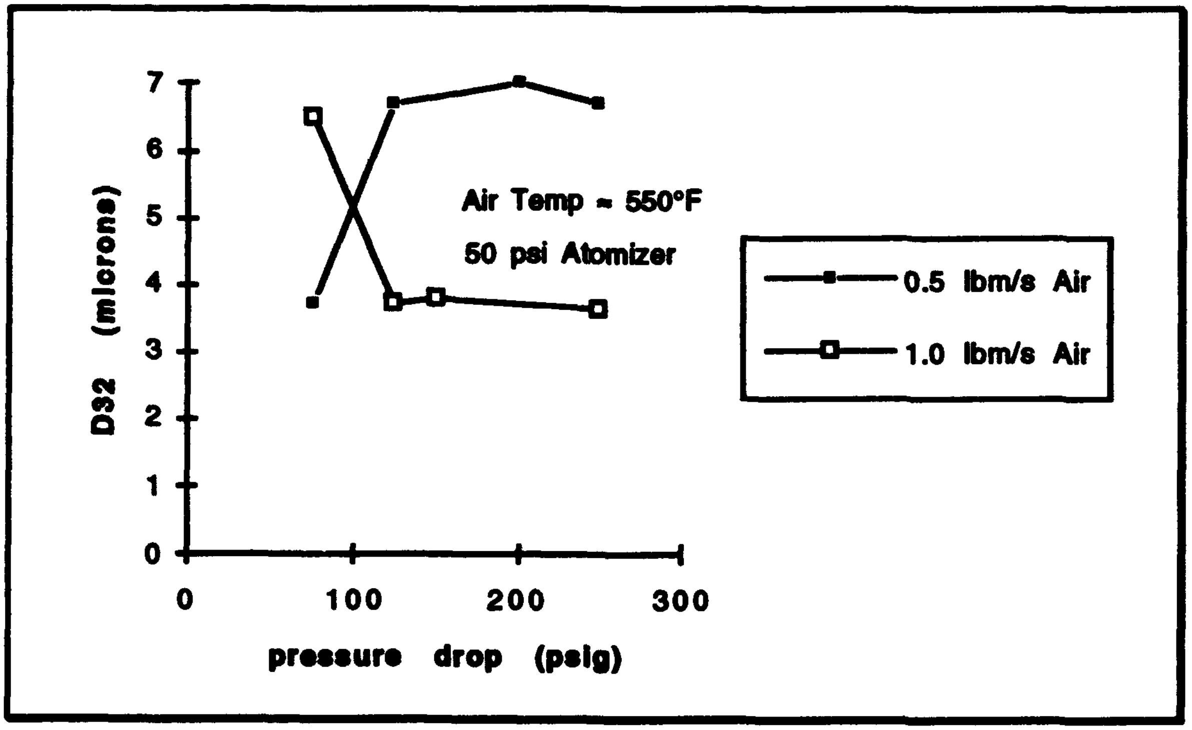

Figure III-3 Effects of Air-Flow Rate on Particle Size

Throughout some of the high temperature runs, a phenomenon known as beam steering may have introduced some error into the Malvern calculations. Beam steering occurs when the laser light refracts due to temperature gradients within the medium carrying the particles, i.e. the hot air. It can be detected, and its effect nullified, by examining the Malvern data display for very large increases or decreases in light intensity from detector ring-to-ring, as this is not a "normal" particle distribution behavior. Once detected, beam steering most often may be nullified by telling the computer to ignore the light on any of the first 10 detector rings. This has the effect of reducing the size of the largest particle capable of being detected since the larger particles are detected by the lower rings. The final column in Tables III-3 and III-4 show on what measurements beam steering was detected and nullified in such a manner. An entry of 5,0 means that the first 10 detector rings were disabled and the data was re-calculated accordingly. It was determined that with the first 10 rings disabled, the maximum particle size capable of being detected was approximately 62 microns. Since runs with similar air-flow rates and pressure drops with no beam steering produced particle sizes no larger than 55 microns, little or no inaccuracy was introduced by this data correction.

For the fuel-tube atomizer, particle size was affected by air temperature as well as air-flow rate as was the case with the 50 psi atomizer. However, particle size was not a function of fuel-flow rate . The mean size, D_{32}, stayed relatively constant over a range of fuel-flow rates as seen in Figure III-4.

It should be noted that the particle sizes produced by all of the atomizers in the hot air, contra-flow environment were quite small (less than 14 microns). Thus, combustion inefficiency due to incomplete fuel vaporization would not be present.

Table III-4 FUEL-TUBE ATOMIZER WITH SURROUNDING AIR FLOW

Mdot Air (lbm/s)	Mdot Fuel (lbm/s)	Air Temp (°F)	D_{max} (μ)	D_{32} (μ)	Vol. Peaks (μ)	% <5.8 (μ)	% Obs.	Kill-Data
0.5	0.02	510	25.4	5.3	<5.8,10	33.6	6	----
0.5	0.04	35	53.0	9.5	<5.8,20 ,32	12.6	71	----
0.5	0.04	511	25.4	5.5	<5.8,10	30.2	0	----
0.5	0.06	510	53.0	5.2	<5.8,10	36.6	29	----
0.5	0.08	510	25.4	5.2	<5.8,10	34.7	5	----
1.0	0.02	522	16.3	3.1	<5.8, 8.5	93.0	16	5,0
1.0	0.04	525	5.8	3.0	<5.8	100	21	5,0
1.0	0.06	35	21.9	4.3	<5.8,10	53.0	0	----
1.0	0.06	525	10.4	3.0	<5.8, 8.5	97.1	34	5,0
1.0	0.08	660	39.5	3.0	<5.8, 8.5	96.7	16	5,0

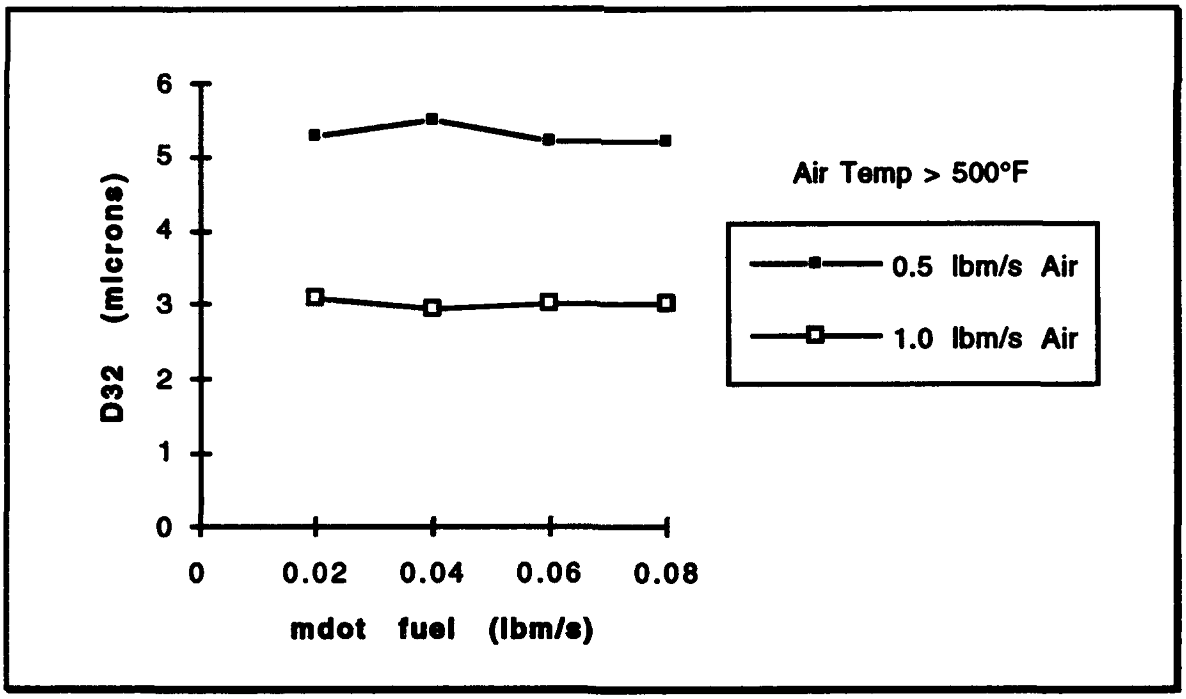

Figure III-4 Effects of Air-Flow Rate on Particle Size for Fuel-Tube Atomizer

B. COMBUSTION TESTS

1. Single Side-Dump Operation

a. 50 psi Poppet Atomizer With and Without Needle Injector

As a control, the combustor was first run with the downstream inlet closed so that all inlet air would arrive through the upstream inlet (100/0 operation). The 50 psi poppet atomizer was installed contra-flow and centered in the upstream inlet as close to the dump plane as possible. This selection was a result of the spray pattern studies discussed in section II-B-1. In order to provide sufficient space for an inlet port cover, the atomizer did not protrude further than 0.5 inches from the upstream side of the dump plane. Throughout the initial battery of tests at 1.0 lbm/s air and over a range of low fuel-flow rates (0.03 to 0.05 lbm/s), the motor would ignite but not sustain without the aid of the igniter torch. Insufficient fuel was penetrating the recirculation zone, so direct fuel injection via the needle fuel injector discussed in section II-B-2 was provided, in conjunction with the poppet atomizer in the upstream inlet. The motor then successfully sustained ignition until fuel shutoff over a range of fuel-air ratios from 0.04 to 0.09. The motor sustained at a fuel-air ratio of 0.03 for only 4 seconds before blowing out. The needle injector was taken out, and the motor sustained ignition at a fuel-air ratio of 0.07 with no apparent change in efficiency. Thus direct injection of approximately 20-25% of the fuel into the dome region can be used to sustain combustion at lean fuel-air ratios.

A second battery of tests was performed in the same configuration (needle injector and poppet installed) but at a reduced air-flow rate of 0.5 lbm/s. The motor successfully sustained ignition at fuel-air ratios from 0.04 to 0.09 at efficiencies slightly lower than those observed at 1.0 lbm/s air. Figure III-5 shows the calculated efficiencies as a function of fuel-air ratio for the 100/0 configuration. Note the rapid drop in combustion efficiency that occurred when the fuel-air ratio decreased below 0.05. This was apparently due to the fuel being concentrated along the center of the inlet dump with subsequent poor mixing in the combustor.

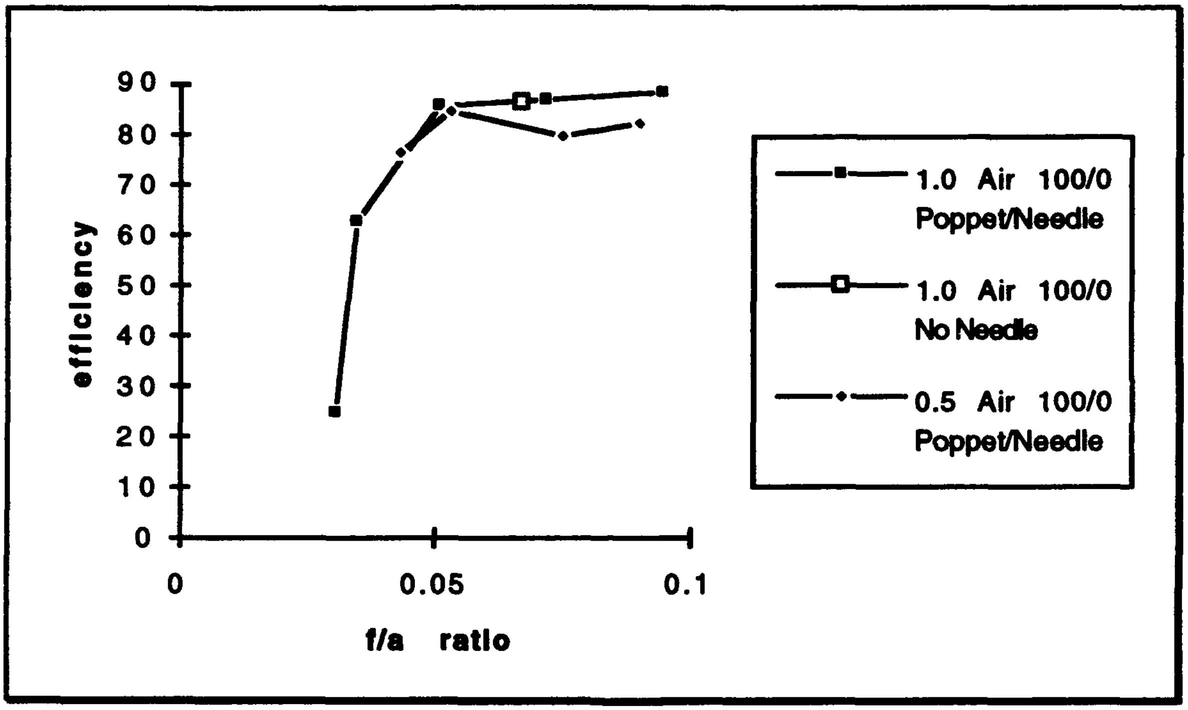

Figure III-5 Single-Dump (100/0) Operation Efficiencies (Poppet)

2. Dual-Inlet Side-Dump Operation

a. 50 psi Poppet Atomizer With and Without Needle Injector

Throughout the remaining combustion tests, the downstream inlet was opened, allowing equal amounts of air to enter the combustor through sonic chokes placed upstream in each inlet (50/50 operation). The first series of tests were conducted at an air-flow rate of 1.0 lbm/s. The needle injector was installed along with the poppet atomizer as before and the motor successfully sustained ignition at fuel-air ratios from 0.03 to 0.05, at which point it was decided to try the motor without the needle injector. Without the needle injector, the motor sustained ignition at fuel-air ratios from 0.03 to 0.07. This improvement in flammability limits over the single dump operation at lower fuel-air ratio was due to the decreased air flow over the atomizer, allowing the fuel spray to spread to the upstream wall at the forward inlet dump. At a fuel-air ratio of 0.09, the motor failed to ignite, probably because the recirculation zone became too fuel rich to sustain ignition. When the air flow was decreased to 0.5 lbm/s successful ignition could only be achieved at fuel-air ratios up to 0.05. This was expected, as even more fuel penetrated the recirculation zone as a result of less air flowing over the atomizer, making the recirculation zone too fuel rich. Figure III-6 shows the calculated efficiencies for the 50/50 poppet configuration. Although the maximum combustion efficiencies achieved were less than for the single side-dump, higher efficiencies were achieved by the 50/50 operation at the low fuel-air ratios.

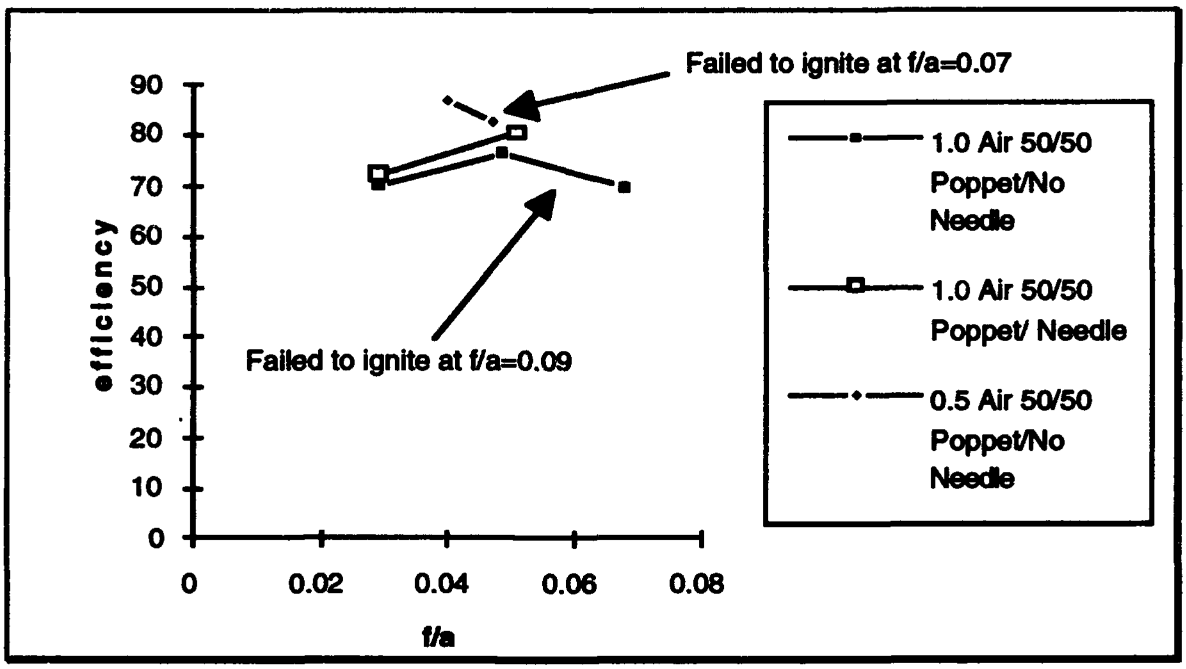

Figure III-6 Dual-Inlet (50/50) Operation Efficiencies (Poppet)

b. 50 psi Poppet Atomizer and Fuel-Tube Atomizer Combined

The dual-inlet operation of the combustor achieved sustained ignition over a wider range of fuel-air ratios at the higher air-flow rate, but not at the lower air-flow rate, since too much fuel was penetrating the recirculation zone. Also, large pressure oscillations of approximately 25-50% of the average chamber pressure, at a frequency of approximately 150 Hz, were present in the dual inlet mode, though oscillations of only 10% were present in the single-dump mode. This meant that an instability in the motor developed when changing the configuration from single to dual-inlet operation. The oscillations were the largest as a percent of the average chamber pressure at the lower air-flow rate of 0.5 lbm/s. A redistribution of fuel was attempted to suppress the pressure oscillations and to keep the recirculation zone from getting too fuel rich at the higher fuel and lower air-flow rates. The fuel-tube atomizer discussed in section II-2 was installed in the downstream inlet with the poppet atomizer still in the upstream inlet. A separate cavitating venturi was installed upstream of each of the fuel atomizers to ensure a steady fuel-flow rate. Approximately 68% of the total fuel flow was directed to the poppet atomizer in the upstream inlet, with the remaining 32% sent to the downstream inlet via the fuel-tube atomizer. The lowest obtainable fuel flow with two venturis flowing, was 0.062 lbm/s. At a fuel-air ratio of 0.062, the motor sustained ignition and the pressure oscillations were negligible, though at higher fuel-air ratios the oscillations became large and erratic. Figure III-7 shows the calculated efficiencies for the combined atomizer configuration. The observed efficiencies in this configuration were slightly less than the 100/0 poppet-only configuration. This was most probably due to an insufficient residence time for the fuel injected in the downstream inlet, causing more of the fuel to escape out the nozzle unburned.

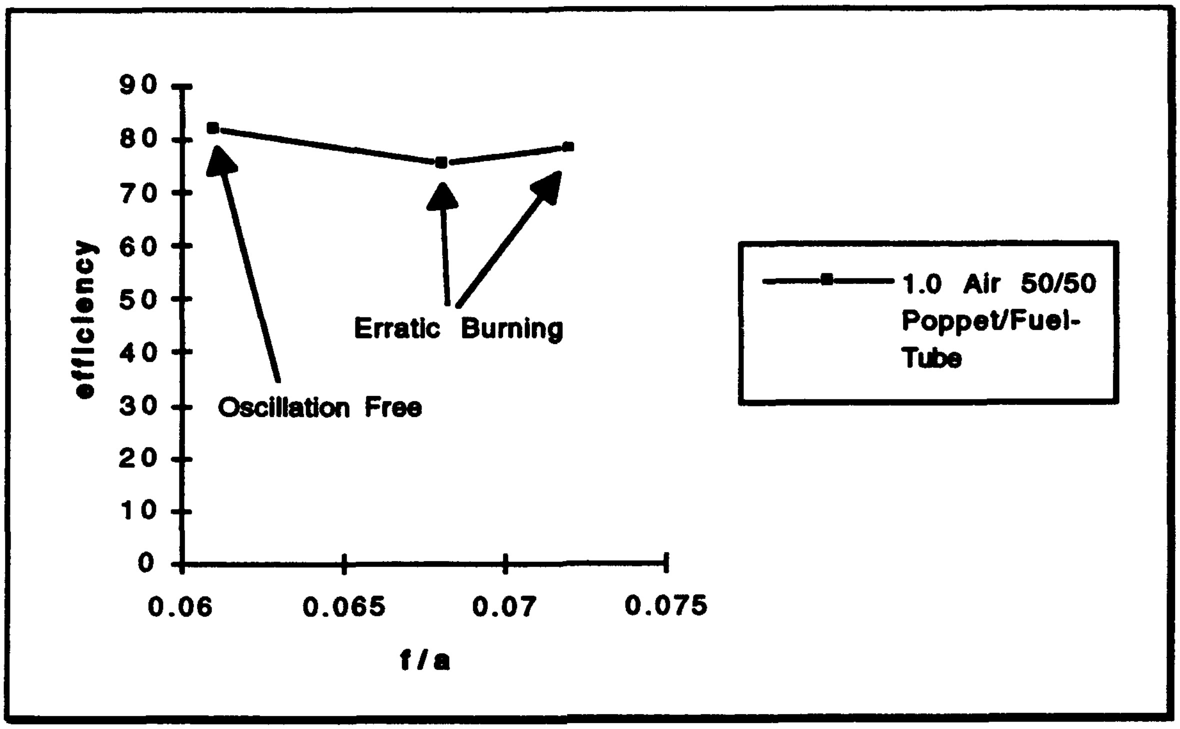

Figure III-7 Dual-Inlet Efficiencies (Poppet/Fuel-Tube Combination)

c. Fuel-Tube Atomizer Only

For comparison to the poppet atomizer, the fuel-tube atomizer was installed contra-flow in the forward inlet the same distance away from the dump plane. Tests were run with the dual-inlet configuration at air-flow rates of 1.0 lbm/s and 0.5 lbm/s over varying fuel-flow rates. Figure III-8 shows the calculated efficiencies for the 50/50 fuel-tube only configuration. For the 1.0 lbm/s air tests at the lower fuel-air ratios (.03 to .05), the efficiencies were slightly higher than those with the poppet-only installed, though slightly lower at the higher fuel-air ratios near .07. The motor also ignited at a fuel-air of 0.09, which was not the case with the poppet only configuration. At a reduced air-flow rate of 0.5 lbm/s and a fuel-air ratio of 0.05, the poppet atomizer did perform better than the fuel-tube. This was probably due to the fact that the fuel-tube depended on the air-flow rate for atomization and would, therefore, perform worse as the air flow was decreased. The poppet exhibited its own atomizing qualities even with no air flow and could, therefore, atomize the fuel well in a low air-flow condition. At the lower fuel-flow rates, or higher air-flow rates, the poppet atomizer fuel spray pattern did not spread completely to the upstream forward inlet wall, and may not have supplied the recirculation zone with enough fuel. Whereas the fuel-tube atomizer always had fuel spraying out of its lower holes (those closest to the upstream wall of the forward dump) at any fuel or air-flow rates. The recirculation zone would, therefore, always be supplied with at least some fuel. The same 150 Hz pressure oscillations were observed just as in the poppet atomizer test runs. The largest oscillations, as a percentage of the average chamber pressure, occurred at the lower air-flow rate.

In an attempt to quell the motor instability, the aero-grid discussed in section II-2 was installed in the forward inlet, approximately 7 inches upstream of the dump plane. This was done in an attempt to decouple the inlet flow from the combustor. Combustion tests were conducted at 0.5 and 1.0 lbm/s air-flow rates. Negligible differences were noted in both the efficiency and the pressure oscillatory behavior, which suggests that the instability was the result of fuel burning in the shedding vortices at the inlet dump plane.

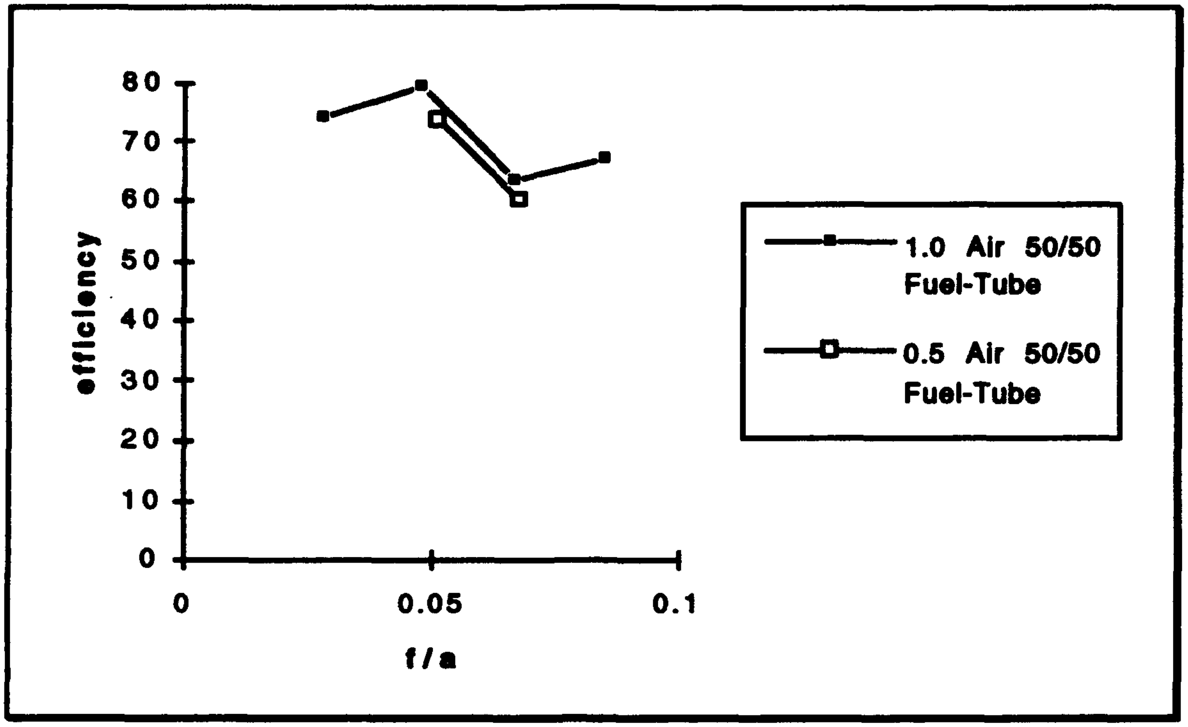

Figure III-8 Dual-Inlet Efficiencies (Fuel-Tube only)

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Fuel atomizers operated under ambient-air conditions produced sprays that were high aque to laser beams, making particle sizing difficult. Under these conditions, poppet atomizers produced mean diameters (D_{32}) between 30 and 80 microns, decreasing in size with increasing fuel-flow rate. The fuel cone spray angle was 65±5°, independent of poppet atomizer model and fuel-flow rate.

When operated in a typical motor environment, (contra-flowing in hot, high velocity air) the mean particle sizes produced by poppet and fuel-tube atomizers were greatly reduced (less than 14 microns) and practically independent of the fuel-flow rate. Increasing air temperature and/or flow rate also decreased D_{32}. The latter also greatly increased the mass percentage of particles with diameters less than 6 microns.

With these excellent atomization qualities, any combustion inefficiency would be due to poor mixing of the fuel and air in the combustor. This mixing was shown to be strongly influenced by the fuel distribution within the inlet duct.

Most of the total fuel flow was found to be required near the inlet duct walls. Fuel was necessary on the upstream side of the forward inlet in order to supply the recirculation zone with an adequate fuel-air ratio. The fuel on the downstream side was best mixed with the air in the combustor. Fuel injected in the center of the inlet duct apparently did not mix well in the combustor and significantly reduced the combustion efficiency. Central injection of the fuel in the inlet duct, as used in this investigation, resulted in poor lean-flammability limits in the single side-dump configuration. Diverting approximately 20% of the fuel directly into the recirculation zone was found to significantly improve the lean-flammability limits.

With the dual-in-line inlets operated with fuel injection only in the upstream inlet, direct fuel injection into the dome region was not required in order to sustain combustion at the lean fuel-air ratios. In addition, combustion efficiencies under lean conditions were significantly greater than for the single-side-dump configuration.

Low frequency pressure oscillations (≈150 Hz) were present in all tests, but had low amplitudes (less than 10%) for the single side-dump where the fuel was most often not reaching the inlet walls. The oscillations were not at the first longitudinal mode of the combustor. High amplitude oscillation (P'/Pc = 25 to 50%) occurred for all dual, in-line side-dump tests when the fuel was injected only into the upstream inlet. Distributing the energy release by injecting fuel into both inlets eliminated the instabilities at lean fuel-air ratios but resulted in erratic burning at higher fuel-air ratios. The latter may have resulted from a coupling between the two combustion zones.

Installation of an aero-grid with an area blockage of 39% just upstream of the fuel injection should have effectively decoupled the inlet from the combustor. The fact that the oscillations persisted indicated that they probably were the result of periodic energy release in the vortices shedding at the inlet dump.

The above discussion indicates that for good flammability limits and high combustion efficiency, the fuel should be distributed near the wall of the inlet duct, but for preventing oscillatory combustion, it should be near the center of the inlet flow. This suggests that to have good performance free of large pressure oscillations, an aero-grid at the dump plane will usually be required to disrupt the vortex shedding. However, distributing the combustion by injecting in two in-line inlets also shows promise for reducing oscillations.

The combustion efficiencies obtained in the present investigation were 5 to 10% below desired levels. With two in-line dump inlets, it appears that the downstream dump should be at a steeper angle (≈60 to 90°), in order to increase mixing.

B. RECOMMENDATIONS

1. For future investigations, a longer dome length of at least 1 to 1.4D should be used in an attempt to achieve better flame holding at the higher fuel-air ratios.

2. Install a second poppet or fuel-tube atomizer contra-flow in the downstream inlet, with less than 30% of the fuel directed to the downstream atomizer, to provide distributed combustion while, at the same time, increasing the dump angle to improve mixing and combustion efficiency.

3. Install an aero-grid at each dump plane to suppress the vortex shedding that is most likely causing the instability during the 50/50 operation.

4. Modify the fuel-tube injector to inject most of the fuel near the upstream and downstream walls of the inlet duct, in order to improve flammability limits and combustion efficiency.

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